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Evaluation of the LWVD Luminosity for Use in the Spectral-Based Volume Sensor Algorithms

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14. ABSTRACT

VibroMeter, Inc. (VMI) and the Naval Research Laboratory (NRL) are developing a commercially viable implementation of the Volume Sensor Prototype. An integrated sensor suite and local data fusion algorithms are being designed as the Volume Sensor Detection Suite (VSDS). As an example of potential inter-component data fusion for the VSDS, the Long Wavelength Video Detection (LWVD) Component Luminosity was investigated as a substitute for the near-infrared (NIR) sensor element in the Spectral-Based Volume Sensor (SBVS) component of the VSDS. The LWVD Luminosity data stream can be used to produce an effective 3-component SBVS configuration for the VSDS with only the UV and IR sensor elements from the SBVS Component Prototype. The current recommendation for the SBVS configuration of the VSDS is a UV/IR, an NIR/UV/IR, or an LWVD/UV/IR configuration, depending on the VSDS data fusion component's tolerance for increased probability of false alarm (P_{fa}) with increased probability of detection (P_d) in different event categories and on the specific intended applications.

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ACRONYMS USED

Acronym	Definition
ADC	Advanced Damage Countermeasures Program
ASCT	Acoustic Detection System
B/W	Black and White
CCD	Charge Coupled Device
COTS	Commerical, Off-The-Shelf
CVN21	Future Aircraft Carrier, CVN 21. Formerly known as CVNX
CVNX	Carrier Vehicle, Nuclear Experimental
CVNX	CVN21 Fire Threat to Ordnance Test Series 2
DAQ	Data Acqusition (Hardware)
DC	Damage Control
DD(X)	DD(X), 21st Century Destroyer. The Navy's future multi-mission surface combatant. Also a series of shipboard testing conducted in 2005 on the ex-USS Shadwell
FA	False Alarm
FM	Fusion Machine
FNC	Future Naval Capability, sponsored by ONR
FOV	Field Of View
FWHM	Full-Width at Half-Maximum, a measurement of the width of a spectral peak
IR	Infrared. In this document, IR refers to the mid-IR, around 4.4 μm.
LP	Longpass (filter), passes wavelengths greater than a cutoff wavelength
LWVD	Long Wavelength-response Video Detection
MV	Machine Vision
NIR	Near InfraRed
NRL	U.S. Naval Research Laboratory
OFD	Optical Flame Detector
ONR	Office of Naval Research
PC	Personal Computer
PD	PhotoDiode
P_d	Probabilty / Percentage of Detection (# Correct Detections / Total of Sources)
P_{fa}	Probabilty / Percentage of False Alarm (# FAs / Total # of Sources)
SBVS	Spectral-Based Volume Sensor
UV	Ultraviolet
VID	Video Image Detection
VID(S)	Video Image Detection (System)
VMI	Vibro-Meter, Inc.
VS	Volume Sensor
VSCS	Volume Sensor Communications Specification
VSDS	Volume Sensor Detection Suite
VSNP	Volume Sensor Nodal Panel
VSP	Volume Sensor Prototype
VS1	Volume Sensor Test Series 1
VS2	Volume Sensor Test Series 2
VS3	Volume Sensor Test Series 3
VS4	Volume Sensor Test Series 4
VS5	Volume Sensor Test Series 5

EXECUTIVE SUMMARY

Under sponsorship from the Office of Naval Research (ONR), Vibro-Meter, Inc. (VMI) and the Naval Research Laboratory (NRL) are currently developing a commercially viable implementation of the Advanced Volume Sensor Prototype previously developed by NRL under ONR's Future Naval Capabilities program, Advanced Damage Countermeasures. An integrated sensor suite and local data fusion algorithms are being designed as the Volume Sensor Detection Suite (VSDS). As an example of potential inter-component data fusion for the VSDS, the Long Wavelength Video Detection (LWVD) Component Luminosity was investigated as a substitute for the near-infrared (NIR) sensor element in the Spectral-Based Volume Sensor (SBVS) component of the VSDS. This report documents the analysis and results of a systematic study of this configuration.

Based on the analysis presented in this report, the LWVD Luminosity data stream can be used in lieu of the NIR data stream to produce an effective 3-component SBVS configuration for the VSDS with only the UV and IR sensor elements from the SBVS Component Prototype. The current recommendation for the SBVS configuration of the VSDS is a UV/IR, a NIR/UV/IR, or a LWVD/UV/IR configuration, depending on the VSDS data fusion component's tolerance for increased probability of false alarm (P_{fa}) with increased probability of detection (P_d) in different event categories and the specific details of the planned installation.

The UV/IR configuration is recommended for situations and/or data fusion algorithm implementations with little tolerance for potential false alarm events. One example might be in a high-value ship compartment where the release of autonomic fire suppression agents for a non-fire event would be considered unacceptable. The UV/IR configuration exhibits the lowest P_{fa} of the studied configurations, but at the expense of a lower P_d.

For situations and / or data fusion algorithm implementations where there is a higher tolerance for potential false alarm events, the NIR/UV/IR configuration is recommended. With the addition of the photodiode sensor, a 15% increase in P_d is achieved for the series of simulated damage control (DC) events investigated in this report but at the cost of a 5% increase in P_{fa}. This configuration would be appropriate in conditions where the data fusion algorithm implementation in the VSDS can successfully use the fusion of multiple data sources to screen out the additional false alarms from the SBVS or in situations where the DC response would be relatively low-cost such as dispatching ship's forces to investigate further.

The LWVD/UV/IR configuration offers intermediate performance between the other two configurations in terms of sensitivity and specificity. Without expanding the sensor hardware requirements for the VSDS, the P_d for the investigated test cases is increased by 10% compared to the reference UV/IR configuration. The increased P_d does come at significant expense in P_{fa}, with an 11% increase over the UV/IR configuration. A significant fraction of these potential false alarms results from welding test case scenarios, in which there is also a response from the SBVS WELDING EVENT algorithm.

Evaluation of the LWVD Luminosity for Use in the Spectral-Based Volume Sensor Algorithms

1. INTRODUCTION

The Advanced Volume Sensor (VS) Project was one element of the Office of Naval Research's (ONR) Future Naval Capabilities program, Advanced Damage Countermeasures. This program sought to develop and demonstrate improved damage control (DC) capabilities to help ensure that the recoverability performance goals for new ship programs, such as the CVN21 family of ships, could be met with the specified manning levels and damage control systems. Using a multi-sensory approach, the Naval Research Laboratory (NRL) is developing new detection capabilities for DC in the shipboard environment. Conventional surveillance cameras, which are currently being incorporated into new ship designs, provide the basis for the VS project. Video Image Detection (VID) is a technology for the remote detection of events within the camera's field of view (FOV) by applying image analysis, or machine vision, techniques to the video image. Optical sensor systems sensitive to radiation outside the visible spectrum and acoustic sensors have been developed in combination with the VID technologies to produce an overall sensor system that is able to provide a broad range of situational awareness for the sensor's entire field of view. The use of remote sensing techniques removes the drawback of typical smoke and fire detection systems that they rely on diffusion of gases, particles, or heat to the detector. A Volume Sensor Prototype (VSP) was developed at NRL to provide an affordable, real-time, robust, and remote detection sensor system that provides detection and classification of DC conditions such as fire, explosions, pipe ruptures, and compartment flooding. The VSP generates alarm notifications for action by the Damage Control Assistant and other available damage control systems based on the detected event. The VSP was successfully demonstrated in simulated shipboard conditions in several test series [1–4] conducted on the ex-USS *Shadwell* in Mobile, AL [5].

The Spectral-Based Volume Sensor (SBVS) was designed to detect fire, smoke, and other hazardous conditions using optical methods outside the visible region of the electromagnetic spectrum [6]. The sensors developed within the SBVS are intended to be used in conjunction with and to augment the performance of the core VID technology of the VSP. The VID systems are generally better at identifying smoke than fire [7], so a primary goal of the SBVS has been to provide better detection for flame and fire. An important constraint in the VS project is that the eventual system must be affordable with a target unit cost of $2,000. This precludes the use of more obvious solutions such as mid-infrared (IR) cameras because the per-unit price is too high (> $10,000 per unit). Two avenues have been pursued in parallel within the SBVS. One approach employs long wavelength video detection (LWVD), emphasizing the benefits of spatial resolution and near infrared imaging afforded by readily available, inexpensive video cameras. Descriptions and results of the LWVD system are provided in other reports [8,9] and in a patent [10]. The second avenue, referred to as the Spectral-Based Volume Sensor (SBVS) Component, utilizes single-element optical detectors operating in several narrow spectral regions from the IR to the ultraviolet (UV) that correspond to the wavelengths of several peak flame emissions.

Initial laboratory and shipboard testing of the VSPs in 2004 – 2005 was extremely successful. The Volume Sensor Detection Suite (VSDS) prototype development effort is an ongoing effort funded by the U.S. Congress in 2008 through ONR. Vibro-Meter, Inc (VMI) and NRL's VSDS prototype effort is focused on the development of a preproduction VSDS unit in a single package that is well positioned to become a future commercial product. The VSDS will serve as the front-line sensor head in ship compartments and will contain the sensor elements and a local data fusion algorithm. Larger scale

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situation awareness will be provided by Volume Sensor Nodal Panels (VSNP) that concentrate signals from multiple VSDS. The design and development of the VSDS involves the evaluation of each sensor element in terms of added value to the performance of the VSDS and the associated cost to incorporate that element. The development of commercial-ready VSNP components and an overall VSP will be a future effort.

The original SBVS Component Prototype consisted of 5 optical sensor elements with coverage ranging from the UV to the infrared (IR). During the requirements design phase of the VSDS prototype, a concerted effort was made to reduce the number of sensor elements to a minimum number to reduce the complexity and cost of the VSDS while maintaining the performance of the SBVS algorithms [11]. Four different potential SBVS configurations were considered for inclusion in the VSDS. The UV/IR configuration offered the lowest sensor element count, the lowest probability of false alarm (P_{fa}), but the lowest probability of detection (P_d) of the 4 configurations. The original SBVS configuration had a significantly higher P_d but at the expense of a higher P_{fa}. The two configurations in which either of the SBVS Component Prototype's near-infrared (NIR) photodiodes (PD) were retained in addition to the UV and IR sensors offered intermediate P_d and P_{fa} results. Based on these results, an initial UV/IR configuration was selected for the VSDS. A VSDS mock-up based on this configuration was built by VMI in 2005 for testing and demonstrations and is discussed in Section 7.1.

The effective wavelength coverage of the LWVD camera and filter is from 720 nm to 1100 nm. The center wavelengths of the two PD sensor elements in the SBVS Component Prototype are 766.5 and 1050 nm, respectively. Given the overlapping coverage of the LWVD and SBVS sensor elements, this report examines the feasibility of using the LWVD Luminosity data stream in lieu of one of the SBVS PD sensor elements in the SBVS event algorithms. Therefore, an effective 3-component SBVS configuration for the VSDS could be constructed using the SBVS UV and IR sensor elements and the LWVD camera.

The organization of this report is as follows. Sections 2 and 3 briefly discuss the SBVS Component Prototype hardware and event detection algorithms, respectively, as they have been tested in Volume Sensor Test Series 3 – 5 [1-4]. Sections 4 and 5 briefly discuss the LWVD Component Prototype hardware and event detection algorithms, respectively, as they have been tested in Volume Sensor Test Series 3 – 5. Section 6 provides a brief description of the VS4 Test Series, the data from which provided the basis of the analysis described in this report. Additional information can be found in Reference 2. Section 7 discusses the development of the VSDS prototype and the supporting additional analysis of the SBVS event algorithms associated with this effort. Sections 8 give the recommendations for the development of the VSDS prototype. Section 9 contains the references cited in this document. Appendix A contains the complete definitions of the SBVS EVENT algorithms as demonstrated in the VS5 [3] and DD(X) Test Series [for example, 4]. Appendix B documents the finalized calibration factors for the 10 existing VSP units. Appendix C documents the parameter values for the various SBVS configurations discussed in Reference 11 and in this report.

2. SBVS COMPONENT PROTOTYPE HARDWARE

The SBVS Component Prototype is described in detail elsewhere [12] and is only discussed briefly here. Each SBVS Component Prototype sensor suite is composed of two units, the VIS/IR unit and the UV unit. A typical installation of a SBVS Component Prototype sensor suite for the VS5 Test Series is shown in Figure 2-1. The VIS/IR unit contains three Si photodiodes (PDs) with interference filters centered at 590.0 (Na), 766.5 (K), and 1050.0 (NIR) nm (bottom unit, starting from the right in Figure 2-1), each with a full-width at half-maximum (FWHM) band width of ~10 nm. Each unit has a mid-IR

(IR) detector installed with a central operating wavelength of 4.4 μm (bottom unit, left-hand element). Several units have a second IR detector with a central operating wavelength of 2.7 μm (2.7 μm + 4.4 μm for sensor suite #53). The data from the second IR detector are not currently used by any algorithm and, where present, were recorded only for future research and development. The UV units (upper unit in Figure 2-1) are designed around a standard UV-only optical flame detector (OFD) (Vibrometer, Inc.). The OmniGuard 860 Optical Flame Detector (Vibrometer, Inc.) used in the original SBVS Testbed contained the same UV sensor. At present, nine pairs of VIS/IR and UV units and a single VSDS mock-up unit have been fabricated. As outlined in a previous report [13], a distributed-architecture data acquisition system was designed and implemented for the SBVS Component Prototype of the VSP using the FieldPoint line (National Instruments) of data acquisition equipment.

Figure 2-1 – Typical installation of the SBVS Component Prototype as tested in VS5 Test Series. The UV unit is positioned above the VIS/IR unit. See the text for a description of the individual elements.

3. SBVS COMPONENT PROTOTYPE ALGORITHMS

Event detection algorithms for five events were implemented for real-time use of the SBVS Component Prototype. The development of these algorithms is presented in Reference 14. After Test Series 4, a retrospective analysis [11] was undertaken to further refine and improve the performance of the SBVS Component Prototype as part of the VSDS prototype development. These events are: EVENT, PDSMOKE, FIRE, FIRE_FOV, and WELDING. The EVENT was conceived as a generic trigger, indicating that some, currently unclassifiable event is occurring in the FOV of the sensor. The PDSMOKE event makes use of long-time-scale deviations observed in the 590.0 nm channel data that were not correlated with flaming events to detect and classify smoke within the sensor FOV. The algorithms for FIRE and FIRE_FOV detection compare the measured channel data “spectrum,” or the pattern of channel values for the five sensors, to an empirically determined spectrum for a fully involved flaming fire in the sensor FOV for the FIRE_FOV event, or to a more relaxed spectrum for the FIRE event. An algorithm for the positive detection of one type of nuisance, arc welding, was also included. To reduce the algorithm sensitivity to transient signals, a persistence criterion of five seconds was applied to the algorithm outputs (25 seconds for the PDSMOKE algorithm). All raw channel data were recorded

locally on one of the SBVS Component Prototype data acquisition computers. Baseline-subtracted and normalized sensor channel data and algorithm outputs were forwarded to the VSP Fusion Machines (FM) using the VSCS communications protocol.

Appendix A gives a complete listing of the SBVS EVENT parameters and the EVENT algorithm descriptions. See Reference 14 for further details. The FIRE EVENT algorithm definition is:

```
Fire:        IF (Sum_N >= 0.0825) and (7665A >= 0.015) and
             (10500A >= 0.015) and (RefIR/UV >= 1) Then
                   FIRE = TRUE
             Else
                   FIRE = FALSE.
```

As part of the original SBVS algorithm development, a principal component analysis (PCA) was conducted on all of the data channels in the SBVS TestBed. A single principal component was identified, labeled SumN, which is defined as the sum of the scaled signals from the four principal sensor elements in the SBVS Component Prototype: the K and NIR PDs, the UV, and the IR sensors. Procedurally, SumN is defined as:

```
SumN = 7665A + 10500A + (0.1 * RefIR) + UV
```

In Reference 14, the definition of SumN included the 590.0 nm (Na) PD data values. In subsequent algorithm iterations, the Na PD data were completely compartmentalized into the PDSMOKE EVENT algorithm and not used in either the determination of SumN or in the FIRE, FIRE_FOV, or WELDING EVENT definitions.

4. LWVD COMPONENT PROTOTYPE HARDWARE

The details of the LWVD Component Prototype can be found elsewhere [8-10,15], and are only briefly discussed here. A typical installation of an LWVD Component Prototype sensor suite for the VS5 Test Series is shown in Figure 4-1. The NRL LWVD Component Prototype uses bullet-style black-and-white Silicon-based CCD (CCD) surveillance cameras. A custom filter mount was built in-house at NRL to hold 2” diameter long pass (LP) filters. The LP filter only allows wavelengths of light greater than a cut-off wavelength to pass through the filter and to the camera. An LP filter with a cut-off wavelength of 720 nm (Hoya R-72) is typically used in the LWVD system. The video image is then captured by a video analog-to-digital converter. A reference, or background, Luminosity (defined in Section 5) value is taken as the Luminosity of a frame collected after the beginning of data acquisition, typically 30 seconds. The background image associated with this frame is stored as a Windows bitmap file (.BMP) for reference purposes. The time-stamped scaled Luminosity (0 – 1) and alarm count are stored in a data file in real time for archival purposes and later analysis.

Figure 4-1 – Typical installation of the LWVD Component Prototype as tested in VS5 Test Series.

5. LWVD COMPONENT PROTOTYPE ALGORITHM

The LWVD algorithm detects fire and hot object events by comparing the luminosity, L, of the current video frame to the sum of a reference luminosity, L_b, and an alarm threshold, L_{th}. Luminosity is defined [8] as the summation of the intensity of each pixel in the video frame normalized for the image dimensions. Previous testing [8] has shown that a fire event generally increases the luminosity of a video frame by an amount independent of the background illumination. The reference luminosity, L_b, is taken as the luminosity value of a frame collected after the beginning of data acquisition, typically 30 seconds. To mitigate the effects of large variations observed in the background luminosity, a nonlinear relationship between the reference L_b and the alarm threshold is used:

$$L_{th} = 2\sqrt{L_b}$$

which yields proportionally smaller thresholds for larger background luminosities. The LWVD algorithm operates by tracking the number of frames that meet the criteria, $L > L_b + L_{th}$, and generates an alarm when a persistence criteria is met. Persistence is used to discriminate against spurious bright nuisances such as a flash of light or a reflective object rapidly moving through the space. Given the rate of video frame processing, the algorithm's minimum response time for event detection with this threshold is 5 seconds. Since laboratory and recorded tests have a defined end time, a maximum response, or reset alarm time criterion has not been necessary to date. This would be a likely requirement for a deployed monitoring system.

6. VOLUME SENSOR 4 TEST SERIES

6.1. GENERAL INFORMATION

The objective of the VS4 test series [2] was to evaluate prototype sensor suites and alarm algorithms onboard the ex-USS *Shadwell* in preparation for demonstrating VSP systems in FY05. In particular, the tests were designed to assess the developmental progress of the VSP system since the Test Series 3 evaluation in July 2004 and to expand the database of scenarios and sensor measurements. These tests were conducted October 18-29, 2004.

Full-scale experiments were conducted aboard the ex-USS *Shadwell* in Mobile, AL [2]. This test series consisted of small fires, adjacent space fires, various nuisance sources, and pipe ruptures that challenged the detection systems. Two VSPs comprised of three prototype sensor suites, one of the evaluated VIDS, and containing newly-developed data fusion algorithms were installed for the test series. The performance of the VSPs and the VID systems were compared to the response of commercial off the shelf (COTS) smoke detection technologies.

6.2. SELECTED TEST SCENARIOS

The tests were conducted in and around the mock magazine on the 3rd deck of the ex-USS *Shadwell*. The test matrix for the VS4 test series consisted of one hundred (100) test scenarios. A variety of fire, nuisance, pipe rupture, and gas release sources were created to expose the VSPs and spot-type detectors to a range of potential shipboard scenarios. Small fires were used to challenge the detection systems and provide performance results for early detection. A number of the nuisance sources involved people moving about the space. Pipe ruptures were simulated with a range of flow rates and leakage areas to challenge the VSP. Further information on the VS4 test matrix can be found in Reference 2. For the purposes of SBVS algorithm development, 52 exemplar VS4 test scenarios were selected which represented unique, single events relevant to the SBVS. There were three SBVS sensor suites installed in the test space with differing FOVs in the compartment, for a total of 156 data sets. An LWVD camera was collocated with each SBVS sensor suite as shown in Figure 7-1. The test scenarios were broken down into four classes: 20 flaming, 5 welding tests, 8 cutting and grinding, and 19 nuisance test scenarios. The specific tests are identified in Table 6-1 – Table 6-4.

Table 6-1 – Test Series VS4 Selected Flaming Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-001	Oct182004_133159	Flaming Cardboard Boxes with Polystyrene pellets
VS4-006	Oct192004_093503	Flaming Trash Can
VS4-009	Oct192004_130003	Flaming Shipping Supplies
VS4-015	Oct192004_160403	Flaming IPA Spill Fire / Trash bag
VS4-018	Oct202004_102359	Flaming Cardboard Boxes with Polystyrene pellets
VS4-022	Oct202004_131459	Flaming Trash Can
VS4-026	Oct202004_163000	Flaming Cardboard Boxes with Polystyrene pellets
VS4-027	Oct212004_082558	Flaming Shipping Supplies
VS4-032	Oct212004_112458	Flaming IPA Spill Fire / Trash Bag
VS4-038	Oct212004_154958	Flaming Trash Can
VS4-043	Oct222004_093358	Flaming Shipping Supplies
VS4-044	Oct222004_103758	Flaming IPA Spill Fire / Trash Bag
VS4-050	Oct252004_084500	Flaming Shipping Supplies
VS4-053	Oct252004_100600	Flaming IPA Spill Fire / Trash Bag
VS4-058	Oct252004_124359	Flaming Cardboard Boxes with Polystyrene pellets
VS4-068	Oct262004_100059	Flaming IPA Spill Fire / Trash Bag
VS4-070	Oct262004_120759	Flaming Cardboard Boxes with Polystyrene pellets
VS4-082	Oct272004_092458	Flaming Cardboard Boxes with Polystyrene pellets
VS4-091	Oct272004_160158	Hot Metal Surface - IPA Spill under Slanted Cab Door
VS4-096	Oct282004_104258	Flaming Trash Can - Camera 4 Tilted Up

Table 6-2 – Test Series VS4 Selected Welding Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-002	Oct182004_143359	Welding
VS4-008	Oct192004_121902	Welding (140 A)
VS4-083	Oct272004_100558	Welding
VS4-090	Oct272004_152358	Welding Preceded by No, Normal, and High Rate Ventilation
VS4-092	Oct272004_163357	TIG Welding Stainless Steel

Table 6-3 – Test Series VS4 Selected Cutting and Grind Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-005	Oct192004_084001	Torch Cut Steel
VS4-014	Oct192004_153802	Grinding Painted Steel
VS4-025	Oct202004_155331	Torch Cut Steel
VS4-035	Oct212004_135258	Grinding Painted Steel
VS4-056	Oct252004_111359	Grinding Painted Steel
VS4-077	Oct262004_150959	Grinding Painted Steel
VS4-085	Oct272004_121658	Grinding Painted Steel
VS4-089	Oct272004_145858	Torch Cut Steel

Table 6-4 – Test Series VS4 Selected Nuisance Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-004	Oct182004_163659	VHF Radio / People Working
VS4-010	Oct192004_134803	Waving Materials
VS4-012	Oct192004_150203	Spilling Metal Bolts
VS4-013	Oct192004_151903	AM/FM Radio / Cassette Player
VS4-016	Oct202004_083159	Engine Exhaust
VS4-019	Oct202004_110859	TV / People Working in the Space
VS4-020	Oct202004_113659	TV with Video
VS4-024	Oct202004_151700	Normal Toasting
VS4-029	Oct212004_100257	People Working in Space - Clean Up from Pipe Rupture
VS4-034	Oct212004_132657	Heat Gun / Space Heater / Fan
VS4-052	Oct252004_095000	People Working in Space - Clean Up from Pipe Rupture
VS4-055	Oct252004_105300	People Working in Space - Clean Up from Pipe Rupture
VS4-064	Oct262004_083159	Engine Exhaust
VS4-066	Oct262004_092359	Aerosol
VS4-067	Oct262004_094359	Flash Photography
VS4-081	Oct272004_091058	Flash Photography with Four People
VS4-098	Oct282004_124158	Space Heater
VS4-099	Oct282004_130058	Toaster
VS4-100	Oct282004_131258	Space Heater

7. SBVS ALGORITHM DEVELOPMENT

The design and development of the VSDS has involved the evaluation of each sensor element in terms of added value to the performance of the VSDS and the associated cost to incorporate that element. This report documents the analysis of the feasibility of the LWVD Luminosity as a replacement for the SBVS NIR PD in the SBVS algorithms for the VSDS.

Additionally, while the existing VSPs had previously demonstrated significant added performance for detection and classification of damage control events, the prototype nature of the system did not allow one to easily envision the potential final products. An example of a complete VSP sensor suite installation for the VS5 test series is shown in Figure 7-1. NRL and VMI determined in 2005 that it would be advantageous to construct a mock-up of a feasible, consolidated production unit device that is as functional as possible. The VSDS mock-up has served as a useful demonstration unit at meetings and presentations. During a magazine test conducted in the Winter of 2008, as part of a new program, the VSPs and the VSDS mock-up were installed for functional demonstration.

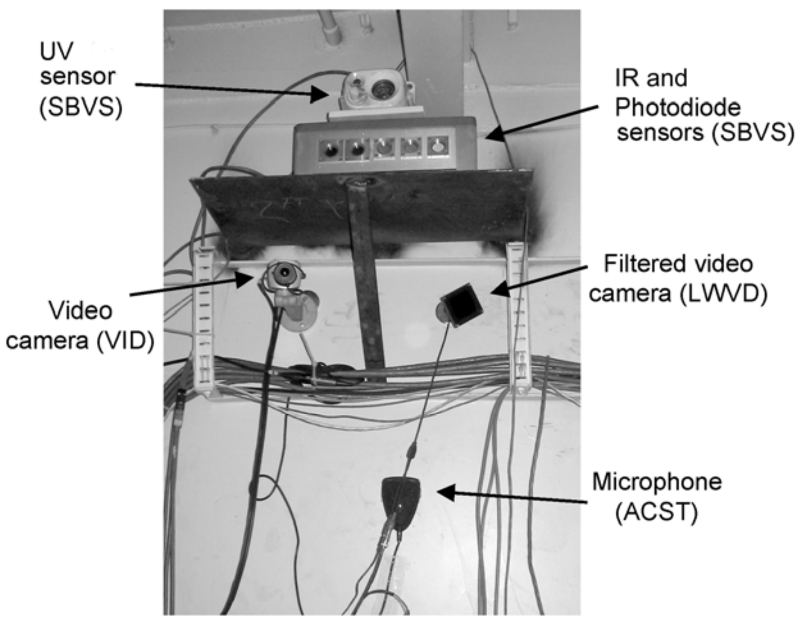

Figure 7-1 – Volume Sensor Prototype Sensor Suite including VIDS, ACST, SBVS, and LWVD components.

7.1. VOLUME SENSOR DETECTION SUITE

The VSDS mockup shown in Figure 7-2 was constructed by VMI with two CCD cameras (one color CCTV and one LWVD filtered B&W camera), the IR and UV sensors from the SBVS Component Prototype, and a microphone. As part of the VSDS prototype development effort, preliminary analyses lead to the down-selection of the SBVS sensor components to only the IR and UV sensors. Based on a recent analysis [11] of the original raw sensor data from Test Series 4 [2], it was determined that a NIR/UV/IR configuration offered nearly the same level of performance as the entire 5-element SBVS Prototype while reducing the overall sensor count. The UV/IR configuration offered excellent P_{fa} results,

but with a 15% reduction in P_d for the test scenarios reviewed. Reference 11 suggested the possibility of using the LWVD Luminosity as a surrogate for one of the silicon photodiode sensors not recommended for inclusion in the VSDS. The normalized outputs of the 766.5 nm (K), 1050 nm (NIR) SBVS PDs and for the LWVD Luminosity are shown for sensor suite #1, test VS4-015, as time series data in Figure 7-3. The normalized responses of the three sensor elements are very similar, as expected for sensor elements with overlapping detection wavelength ranges and for emission sources which are spectrally unstructured [16]. The remainder of this report will discuss analyses conducted to more rigorously explore this possibility.

Figure 7-2 – VSDS mock-up constructed by VMI in 2005.

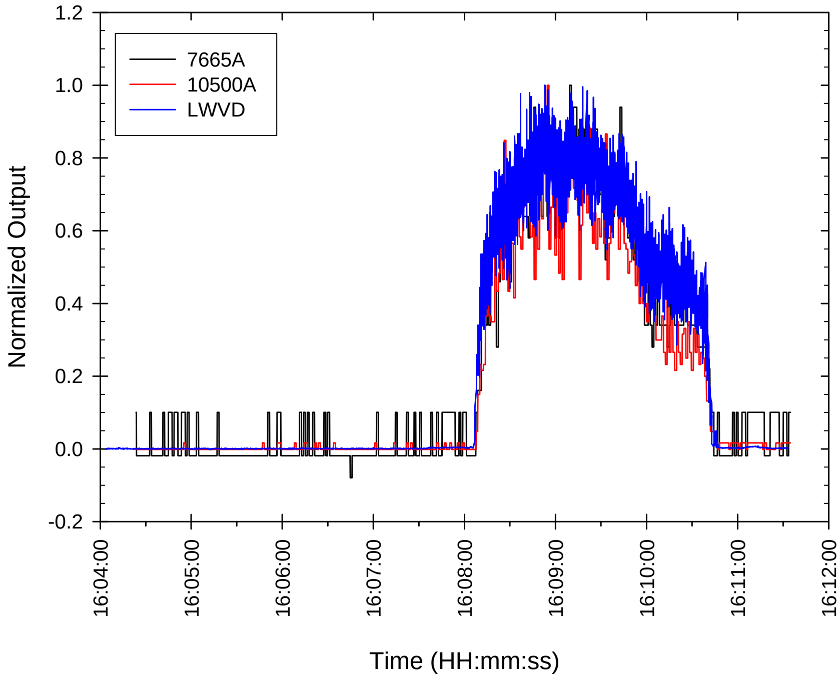

Figure 7-3 – Normalized SBVS and LWVD NIR output time series for VS4-015, Sensor Suite #1.

7.2. DEVELOPMENT TOOLING

To partially automate the data analysis process our retrospective processing software, SBVD_Replay, was modified to include the LWVD data when reprocessing previously collected data files. The software allows sensor calibration and algorithm threshold parameters to be varied to evaluate the impact of these changes. A screenshot of the program operating is shown in Figure 7-4. The current version only functions for archival data files from Test Series 4. The analyses of Reference 11 focused on a select subset of the Test Series 4 (See Section 6.2).

The sensor calibration factors are displayed in the upper left of the screen and are user-editable from within the program. The operator is then able to select which of the six sensor elements will be considered in the reprocessing (lower left of screen). The right-hand side of the screen is devoted to the algorithm thresholds and parameters. The persistence, or duration of an event, required to trigger each event type is displayed in the middle left of the screen. Once the operator has configured the run as desired, the selected data files are reprocessed using the new parameters and a composite output file is generated for all files processed. This program allows the operator to systematically vary a parameter and observe the results easily.

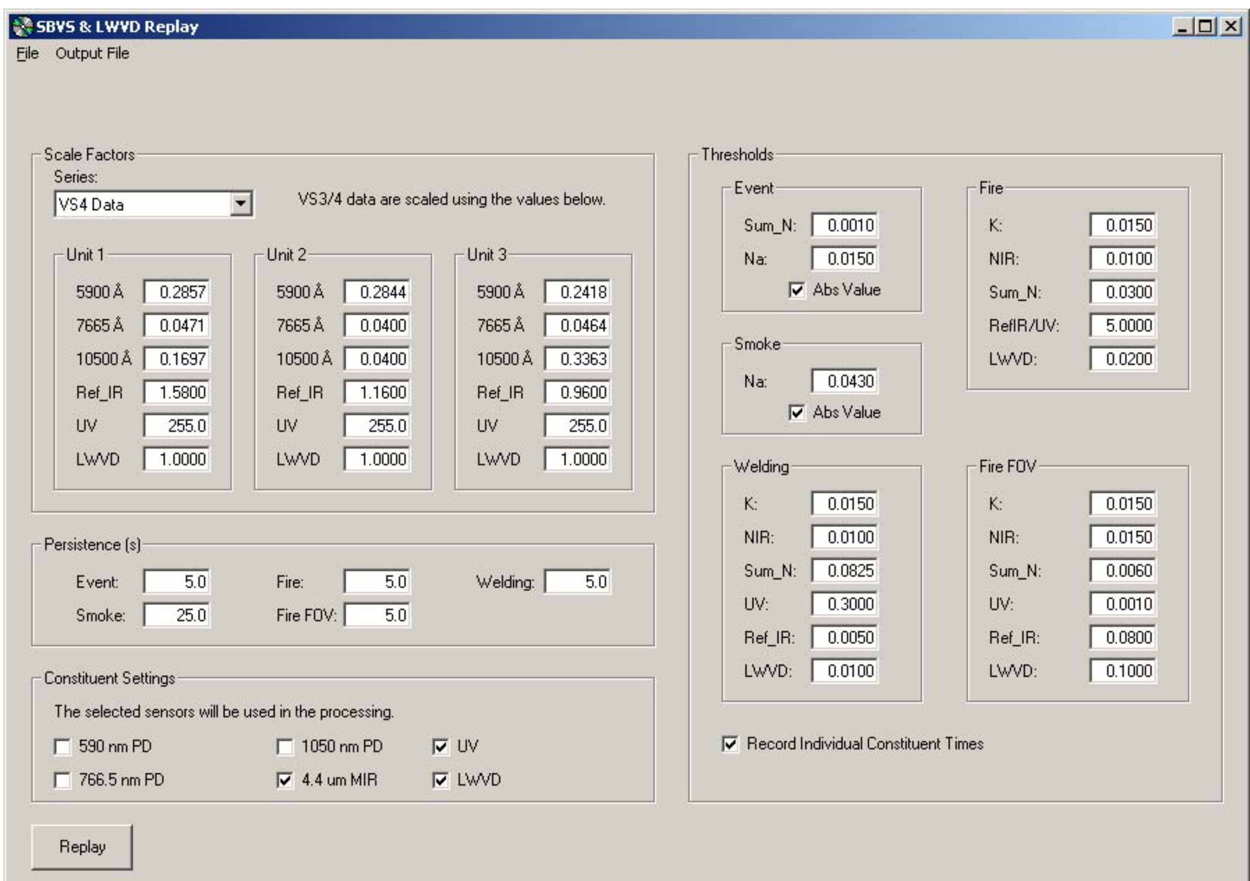

Figure 7-4 – Screenshot of the LWVDSBVS_Replay tool.

7.3. ANALYSIS RESULTS

A detailed examination of the viability of substituting the LWVD luminosity for one of the SBVS NIR PDs was conducted with the goal of mitigating some of the performance loss incurred due to reducing the SBVS sensor count from the original 5 sensors to only the IR and UV sensors. A subset of the VS4 Test Series data archive was selected for analysis as described in Section 6.2. For each algorithm parameter (threshold) outlined in Appendix C and those added for the LWVD data, an individual optimization was conducted as described in Section 5.3.4 of Reference 11. Once each parameter had been individually optimized, a second optimization step was conducted from the recommended values to check for a global minimum. During the initial phases of these analyses, it became clear that the focus of the effort would be on the optimization of the FIRE EVENT. The performance of the FIRE_FOV and WELDING EVENTs in the LWVD/UV/IR configuration was virtually unchanged from that of the other possible configurations and will only be discussed briefly. One caveat that should be kept in mind is that SBVS calibration procedures for the individual units were under development throughout much of the VSP testing. All new analyses discussed in this document use the final VS5 calibration values as listed in Appendix B.

7.3.1. FIRE EVENT

A focused analysis of the performance of the FIRE EVENT comparing the relative performance of an LWVD/UV/IR SBVS configuration for the VSDS using the existing LWVD Luminosity was undertaken.

The SBVS FIRE EVENT algorithm definition can be recast including the LWVD Luminosity and the SBVS UV and IR sensors as:

```
Fire:        IF (Sum_N >= 0.03) and (LWVD >= 0.02) and (RefIR/UV >= 5) Then
                   FIRE = TRUE
             Else
                   FIRE = FALSE.
```

The SumN principal component is then redefined as:

```
             SumN = LWVD + (0.1 * RefIR) + UV
```

From the definition of the FIRE EVENT, several thresholds are apparent and these parameters are varied in this analysis for each potential configuration of the new VSDS. Numerical parameter values given above are the final optimized values for the LWVD 3-element configuration presented in this report.

The performance of this configuration was compared to the four potential configurations for the SBVS portion of the VSDS presented in a previous report [11]. The results for the five configurations are given in Table 7-1 through Table 7-12. In the case of the 4-element SBVS Prototype configuration, results for two different SumN thresholds for the FIRE EVENT are presented as a balance between P_d and P_{fa} considerations. Table 7-1 through Table 7-10 are taken directly from Reference 11 and repeated here for convenience.

The performance (P_d) of the LWVD 3-element configuration (LWVD, UV, and IR sensors) and the SBVS FIRE EVENT algorithm for flaming fire tests (90%, 53 out of 59 tests) is comparable to that of the previously recommended 3-element configurations and lies between that of the K/UV/IR configuration (82%, 48 out of 60 tests) and the NIR/UV/IR configuration (95%, 57 out of 60 tests). There is one fewer

flaming test case for the LWVD 3-elemnt configuration because the LWVD data file for that sensor suite (VS4-044, sensor suite #3, LogFile_1022_103803_3.txt) contained no data and therefore retroactive analysis could not be run for this test case.

The relative false-alarm rejection performance of the LWVD 3-element configuration initially appears discouraging when compared to the other configurations. The LWVD 3-element configuration generated FIRE EVENTS for 53% (8 of 15) of the Welding test cases, 25% (6 of 24) of the Cutting and Grinding test cases, and 0% of the Nuisance test cases, for an overall 15% of the non-Flaming fire test cases. For comparison, the K 3-element configuration performance was 0, 33, and 0%, or 8% overall and the NIR 3-element configuration performance was 0, 38, and 0%, or 9% overall. The results are less discouraging when reviewed by test case category. Both PD-based 3-element configurations only registered FIRE EVENTS for the Cutting and Grinding test cases, for 33 and 38%, respectively. The LWVD 3-element configuration reduces this to 25%. The remaining FIRE EVENT alarms are for Welding test cases where the coincident WELDING EVENTs can take precedence in an overall data fusion algorithm such as those implemented in the VS Data Fusion Machine [17].

Table 7-1 – UV/IR configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	48 / 60	0 / 60	18 / 60	0 / 60
Welding	1 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	0 / 24	0 / 24	0 / 24	0 / 24
Nuisances	3 / 57	0 / 57	0 / 57	0 / 57

Table 7-2 – UV/IR configuration response results by test scenario class

UV/MIR Optimization	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	48	0	0	48
Welding Tests	1	0	15	0
Cutting and Grinding Tests	0	0	0	0
Nuisance Tests	3	0	0	3

Table 7-3 – K/UV/IR configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	49 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	8 / 24	0 / 24	0 / 24	0 / 24
Nuisances	0 / 57	0 / 57	0 / 57	0 / 57

Table 7-4 – K/UV/IR configuration response results by test scenario class

New Opt. - K, MIR, UV	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	49	0	0	49
Welding Tests	0	0	15	0
Cutting and Grinding Tests	8	0	0	8
Nuisance Tests	0	0	0	0

Table 7-5 – NIR/UV/IR configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	57 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	9 / 24	0 / 24	0 / 24	0 / 24
Nuisances	0 / 57	0 / 57	0 / 57	0 / 57

Table 7-6 – NIR/UV/IR configuration response results by test scenario class

New Opt. - NIR, MIR, UV	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	57	0	0	57
Welding Tests	0	0	15	0
Cutting and Grinding Tests	9	0	0	9
Nuisance Tests	0	0	0	0

Table 7-7 – K/NIR/UV/IR, Small SumN configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	59 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	10 / 24	0 / 24	0 / 24	0 / 24
Nuisances	1 / 57	0 / 57	0 / 57	0 / 57

Table 7-8 – K/NIR/UV/IR, Small SumN response results by test scenario class

New Opt. 4 Element - Small SumN	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	59	0	0	59
Welding Tests	0	0	15	0
Cutting and Grinding Tests	10	0	0	10
Nuisance Tests	1	0	0	1

Table 7-9 – K/NIR/UV/IR, Large SumN algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	58 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	9 / 24	0 / 24	0 / 24	0 / 24
Nuisances	0 / 57	0 / 57	0 / 57	0 / 57

Table 7-10 – K/NIR/UV/IR, Large SumN response results by test scenario class

New Opt. 4 Element Large SumN	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	58	0	0	58
Welding Tests	0	0	15	0
Cutting and Grinding Tests	9	0	0	9
Nuisance Tests	0	0	0	0

Table 7-11 – LWVD/UV/IR algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	53 / 59	0 / 59	17 / 59	0 / 59
Welding	8 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	6 / 24	0 / 24	0 / 24	0 / 24
Nuisances	0 / 57	0 / 57	0 / 57	0 / 57

Table 7-12 – LWVD/UV/IR response results by test scenario class

New Opt. - LWVD, MIR, UV	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	53	0	0	53
Welding Tests	8	0	15	8
Cutting and Grinding Tests	6	0	0	6
Nuisance Tests	0	0	0	0

7.3.2. FIRE_FOV AND WELDING EVENTS

Results shown in the previous section demonstrate that it is possible to achieve the same P_d and P_{fa} performance for the LWVD 3-element SBVS Prototype with respect to the FIRE_FOV and WELDING EVENTs in all test scenarios as is expected from the other configurations. Limited optimization of the associated algorithms yielded no improvement in performance. The existing VSP data fusion algorithms [17] rely heavily on the SBVS WELDING EVENT to guard against false alarms generated by the other components, including the other SBVS EVENTs.

8. RESULTS AND RECOMMENDATIONS

One of the current objectives is to reduce the number of sensors in the SBVS Component of the VSP to simplify the VSDS implementation while maintaining as much performance as possible. To this end we have evaluated the consequences of discarding the PDs in our previous report [11] and further characterize eliminating the NIR PDs and substituting the LWVD Component sensor data in this report. We previously reported efforts to optimize the performance of the SVBS Component Prototype of the VSP in terms of detection and DC event classification performance, which included assessing the effect on system performance of removing one or more of the five existing sensor elements. In our previous report, two configurations were identified that offered most of the performance of the optimized, original SBVS. One of these configurations was the combination of the SBVS IR, UV, and one of the SBVS NIR PD sensors. For the VSDS currently under development, there is an even greater desire to reduce the complexity and associated cost of a final production unit, which has prompted us to explore reducing the sensor count further by eliminating the narrowband PD sensors entirely. Recognizing that the LWVD sensor has similar detection properties as the NIR PD sensor, we have evaluated the prospects of

preserving most, if not all, of the system performance when the LWVD sensor data are used in place of the NIR PD sensor data. The LWVD/UV/IR configuration offers performance intermediate between the original configuration with all five sensors and the system without any PDs. Recommendations are made depending on the intended application.

The addition of a third sensor element to the UV/IR SBVS Component Prototype configuration increases the overall system performance for FIRE EVENT detection. Previous studies explored the performance of two possible 3-element configurations based on the original 5-element SBVS Prototype. In each case, the addition of a third sensor element to the UV/IR configuration leads to increased P_d for the FIRE EVENT with increasing P_{fa} (see Section 7.3). The K 3-element combination offers little improvement in the FIRE Event P_d (0.82 vs. 0.80) while doubling the number of false alarms. This combination is not recommended. The NIR 3-element combination offers significant improvement in the FIRE EVENT P_d (0.95 vs. 0.80) while only adding 5 additional false alarms over the UV/IR combination. Especially interesting is that the FIRE EVENT false alarms generated are moved from the nuisance and welding test scenario classes to the cutting and grinding class. Hot work of these types is not typically conducted without significant preparation and system-wide notification in a shipboard environment and any DCA systems would most likely be secured or operating in a special mode to handle this type of work. This reduces the potential severity of the generated false alarms. Clearly there are trade-offs between sensitivity and selectivity. From the data fusion perspective, data from other sources can be used to tailor overall system performance.

The LWVD/UV/IR configuration offers an intermediate performance between the other two 3-element configurations. Without expanding the sensor hardware requirements for the VSDS, the P_d for the investigated test cases can be increased by 10% from the reference UV/IR configuration. The increased P_d does come at significant expense in P_{fa}, with an 11% increase over the UV/IR configuration. A significant fraction of these potential false alarms results from the welding test case scenarios, scenarios where there is also a response from the SBVS WELDING EVENT algorithm. If the situation and the data fusion algorithm implementations are appropriate, the LWVD /UV/IR configuration offers a significant improvement in the potential P_d of the SBVS Component and the overall VSDS with a minimum of hardware requirements.

Based on the analysis presented in this report, the LWVD Luminosity data stream can be used in lieu of the NIR data stream to produce an effective 3-component SBVS configuration for the VSDS with only the UV and IR sensor elements from the SBVS Component Prototype. The current recommendation for the SBVS configuration of the VSDS is a UV/IR, a NIR/UV/IR, or a LWVD/UV/IR configuration, depending on the VSDS data fusion component’s tolerance for increased probability of false alarm (P_{fa}) with increased probability of detection (P_d) in different event categories and contingent upon the specific intended application. The EVENT parameters associated with the five potential SBVS configurations for the VSDS discussed are given in Appendix C.

9. REFERENCES

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APPENDIX A. SBVS EVENT ALGORITHM DEFINITIONS AND PARAMETERS

The finalized SBVS EVENT criteria and parameters as used in the VS5 and DD(X) Test Series were:

```
Event:      If (Sum_N >= 0.0825) or (Abs(5900A) >= 0.015) Then
                  EVENT = TRUE
            Else
                  EVENT = FALSE.
Smoke:      If Abs(5900A) >= 0.043 Then
                  PDSMOKE = TRUE
            Else
                  PDSMOKE = FALSE.
Fire:       IF (Sum_N >= 0.0825) and (7665A >= 0.015) and
            (10500A >= 0.015) and (RefIR/UV >= 1) Then
                  FIRE = TRUE
            Else
                  FIRE = FALSE.
Fire_FOV:   IF (Sum_N >= 0.6) and (7665A >= 0.015) and
            (10500A >= 0.015) and (RefIR >= 0.2) and (UV >= 0.001) Then
                  FIRE_FOV = TRUE
            Else
                  FIRE_FOV = FALSE.
Welding:    IF (Sum_N >= 0.0825) and (7665A >= 0.015) and (10500A >= 0.015)
            and (RefIR < 0.056) and (UV >= 0.175) Then
                  WELDING = TRUE
            Else
                  WELDING = FALSE.
Persistence:
      IF EVENT_TYPE = TRUE
                  EVENT_TYPE.IndexCount = EVENT_TYPE.IndexCount + 1
                  IF EVENT_TYPE.IndexCount > 5[1]
                        EVENT_TYPE.IndexCount = 5[1]
      ELSE
                  EVENT_TYPE.IndexCount = EVENT_TYPE.IndexCount – 1
                  IF EVENT_TYPE.IndexCount < 0
                        EVENT_TYPE.IndexCount = 0
      IF EVENT_TYPE.IndexCount >= Persistence[1]
                  EVENT_TYPE.ALARM = TRUE
      ELSE
                  EVENT_TYPE.ALARM = FALSE.
```

[1] For the PDSMOKE EVENT, the persistence value is 25 seconds, not 5.

APPENDIX B. SBVS SENSOR SUITE SCALE FACTORS

Each of the nine SBVS Component Prototype sensor suites and the VSDS mock-up have individual scale factors for calibration and inter-unit uniformity in response. The factors for the existing units are listed below in Table B-1. There are four generations of units: the original units (S/N 51 – 53), the second generation (S/N 54 and 55), the third generation (S/N 56 – 59), and the VSDS mockup (S/N 21). The RefIR1 scale factors for units S/N 51, 52, and 53 were updated for the DD(X) Test Series conducted during January, 2005 on the ex-USS *Shadwell*.

Table B-1 – SBVS sensor suite scale factors by unit serial number (S/N)

Unit S/N	**51**	**52**	**53[a]**
Unit Type	**VSP**	**VSP**	**VSP**
NaPD	0.2857	0.2844	0.2418
KPD	0.0471	0.0400	0.0464
NIRPD	0.1697	0.0400	0.3363
RefIR1	1.5800	1.1600	0.9600
RefIR2	3.2500	3.2500	3.2500
UV	255	255	255
DD(X)			
RefIR1	5.0380	3.7000	3.0710

[a] Unit S/N 53 has a split interference filter for RefIR2 (2.7 + 4.3 μm)

Unit S/N	**54**	**55**	**56**
Unit Type	**VSP**	**VSP**	**VSP**
NaPD	0.1050	0.1050	0.2600
KPD	0.0038	0.0038	0.0470
NIRPD	0.2530	0.2530	0.2530
RefIR1	2.1000	2.1000	0.5250
RefIR2	3.2500	3.2500	3.2500
UV	255	255	255

Unit S/N	**57**	**58**	**59**
Unit Type	**VSP**	**VSP**	**VSP**
NaPD	0.2600	0.2600	0.2600
KPD	0.0470	0.0470	0.0470
NIRPD	0.2530	0.2530	0.2530
RefIR1	0.5250	0.5250	0.5250
RefIR2	3.2500	3.2500	3.2500
UV	255	255	255

Unit S/N	**21**
Unit Type	**VSDS**
NaPD	0.25
KPD	0.05
NIRPD	0.25
RefIR1	0.3100
RefIR2	3.2500
UV	255

APPENDIX C. SBVS EVENT PARAMETERS BY CONFIGURATION

For each of the five VSDS configurations discussed in this report, the complete listing of SBVS algorithm parameters used in the analyses are given in Table C-1.

Table C-1 – Potential VSDS configuration SVBS algorithm parameter values

	UV/IR	K/UV/IR	NIR/UV/IR	LWVD/UV/IR	K/NIR/UV/IR Small SumN	K/NIR/UV/IR Large SumN
EVENT						
Sum_N	0.001	0.001	0.001	0.001	0.001	0.001
Na						
FIRE						
Sum_N	0.0017	0.0017	0.025	0.03	0.017	0.024
K		0.03			0.0007	0.0007
NIR			0.01		0.01	0.01
RefIR/UV	0.5	0.5	0.5	5	1	1
LWVD				.02		
PDSMOKE						
Na						
FIRE_FOV						
Sum_N	0.006	0.006	0.006	0.006	0.006	0.006
K		0.015			0.015	0.015
NIR			0.015		0.015	0.015
UV	0.001	0.001	0.001	0.001	0.001	0.001
Ref_IR	0.08	0.08	0.08	0.08	0.08	0.08
LWVD				0.1		
WELDING						
Sum_N	0.0825	0.0825	0.0825	0.0825	0.0825	0.0825
K		0.015			0.015	0.015
NIR			0.01		0.01	0.01
UV	0.3	0.3	0.3	0.3	0.3	0.3
Ref_IR	0.005	0.005	0.005	0.005	0.005	0.005
LWVD				0.01		